NASA CONTRACTOR REPORT

NASA CR-1

NASA CR-188

LOAD-BEARING CHARACTERISTICS OF BIAXIALLY PRESTRESSED CERAMIC PLATES

by M. A. Ali, R. D. Chipman, Peter Kurtz, and W. J. Knapp

Prepared under Grant No. NsG-427 *by*
UNIVERSITY OF CALIFORNIA
Los Angeles, Calif.
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1965

LOAD-BEARING CHARACTERISTICS OF BIAXIALLY PRESTRESSED CERAMIC PLATES

By M. A. Ali, R. D. Chipman, Peter Kurtz, and W. J. Knapp

Prepared under Grant No. NsG-427 by
UNIVERSITY OF CALIFORNIA
Los Angeles, Calif.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Office of Technical Services, Department of Commerce,
Washington, D.C. 20230 -- Price $1.00

FOREWORD

The research described in this report, Load-Bearing Characteristics of Biaxially Prestressed Ceramic Plates, is part of the continuing program in Analytical and Experimental Investigation of Ceramic Materials for Use as Structural Elements.

Thanks are extended to F. R. Shanley and M. S. Troitsky for their helpful advice and assistance. Grateful acknowledgement is expressed to the National Aeronautics and Space Administration under whose support (Grant NsG-427) this research was carried on, and to the International Pipe and Ceramics Corporation for their special fabrication of the ceramic plates used.

ABSTRACT

Biaxially prestressed ceramic plates were subjected to transverse loading until failure occurred. The plates were 1/2"x6"x6" in size, and the transverse load was applied normal to the center of a plate face over a 1-1/2" circular area. The load-bearing characteristics of ceramic plates, under the conditions of this study, were greatly improved by biaxial prestressing, giving an optimum increase of almost 700%. An analysis of the loading of a hypothetical uniaxially prestressed beam was presented to explain the main features of the variation of load-bearing capacity with prestress. The stiffness of prestressed plates increased with level of prestress. The failure occurring in a biaxially prestressed plate, by the loading used, was characterized by the formation of a hole by the penetrating ram.

I. INTRODUCTION

The use of ceramics as structural elements is increasing, due largely to the need for materials which may be utilized in a high temperature, oxidizing environment. A promising technique for enhancing the structural utility of ceramics is prestressing. This technique counteracts the inherent weakness in tension of brittle materials by precompressing those elements which will be subject to tension in service. A number of investigations of prestressed ceramic members has been carried on in past years, and continuing studies are in progress (see References). However, present knowledge concerning the characteristics of prestressed ceramics is limited, and further study in this area seems desirable, in order that the structural designer may have available needed basic information.

An interesting question is: How much improvement in load-bearing capacity can be realized by prestressing? (Given the nature of the member, supports, load, prestressing, etc.) The purpose of the work described in this paper was to determine the effect of biaxial prestressing on the static load-bearing capacity of some ceramic plates, for given conditions of supports, loading and prestressing.

II. EXPERIMENTAL

(1) Ceramic Plates

The ceramic members tested were plates nominally 1/2"x6"x6" in size. The plates were manufactured with a high-talc (western type) wall-tile body, using factory production equipment for press-forming and firing. X-ray analysis indicated that the chief crystalline phases present in the fired plates were enstatite, quartz, diopside and feldspar. Some representative property values for these plates were:

Modulus of rupture - 3640 psi ± 270

Compressive strength - 16,000 psi (by A.S.T.M., E6-62, Sec 5)

Modulus of elasticity - 4.4×10^6 psi (by A.S.T.M., E6-62, Sec 11)

Apparent porosity - 20.5% ± 1.2 (by A.S.T.M., C20-46)

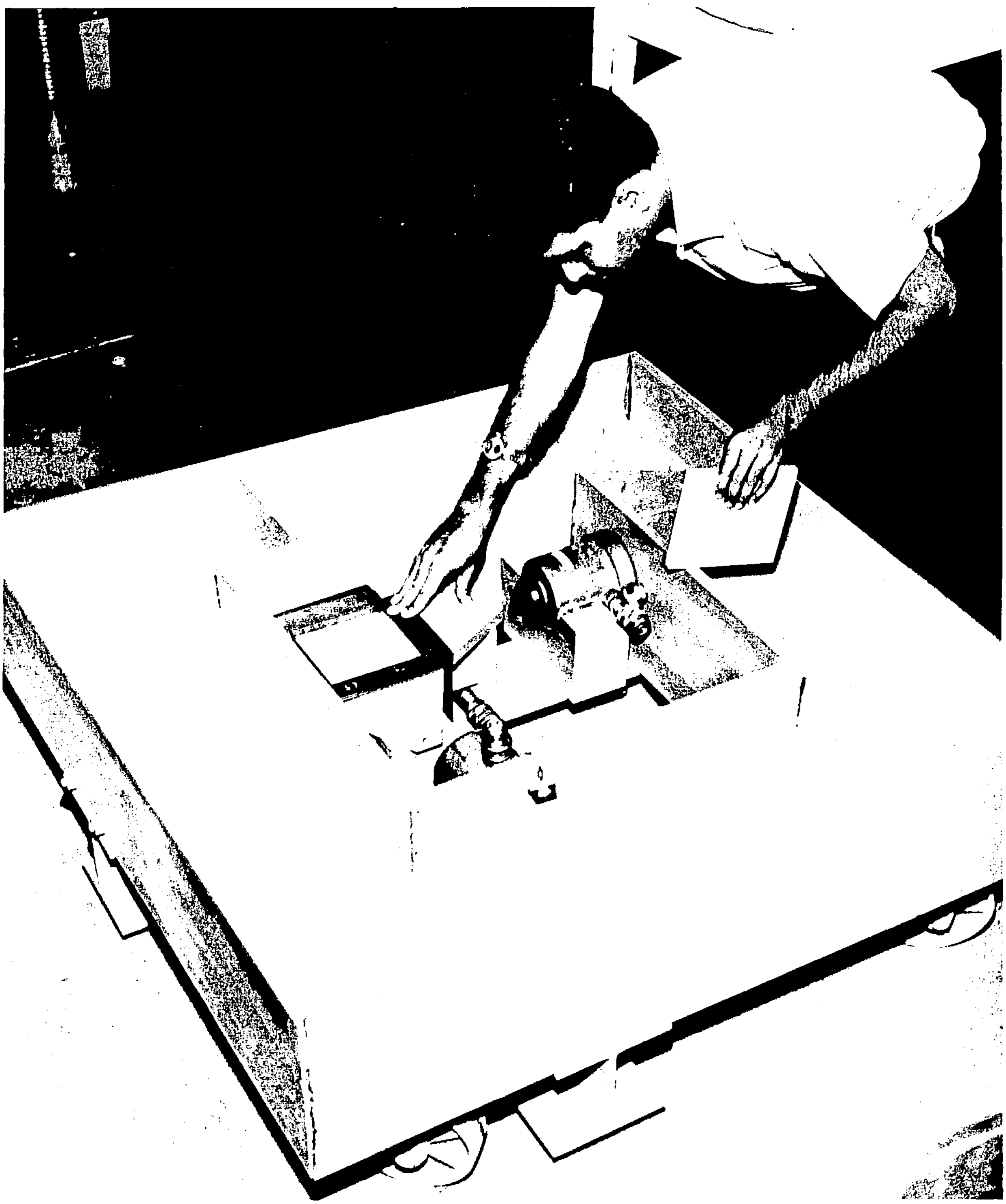
(2) Prestressing Fixture

A fixture, for applying prestressing loads to a ceramic plate, was fabricated, consisting of 10-inch steel I-beams fastened to form a square frame. The frame was supported by crossed 6-inch I-beams (Figure 1). The prestressing loads could be imposed in the x and y directions by two calibrated hydraulic jacks, each of 30 tons capacity. A transverse load could be applied normal to the center of a plate face with a calibrated jack of 10 tons capacity. The prestressing loads were transmitted from the jacks through spherical bearings into grooved bearing blocks, and thence into the test specimen, which is supported edgewise in the grooves. The transverse load was applied over a 1-1/2" circular area at the center of a plate face. Figures 2 and 3 show some details of the nature of supports and loads. Thin, rubberized asbestos gasketing was used to cover all load-bearing surfaces of the ceramic to help distribute loads.

(3) Testing Procedure

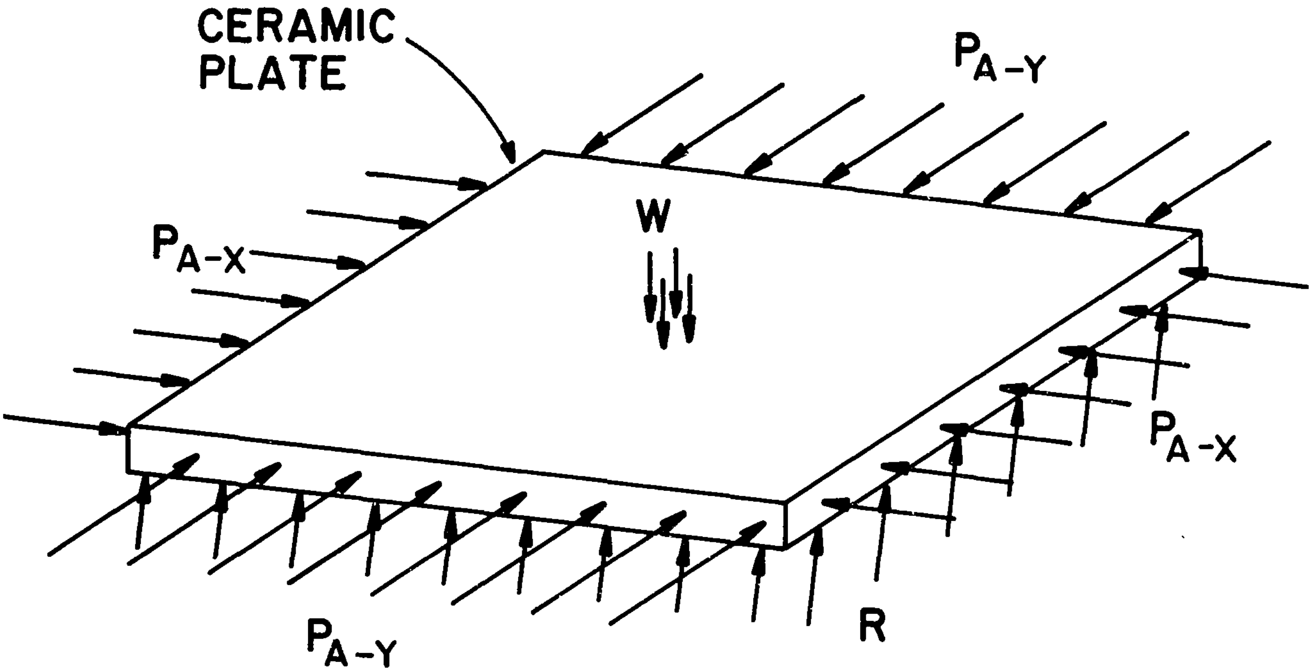
A ceramic plate was placed in the fixture, and biaxial prestressing loads were simultaneously applied with the prestressing jacks until the desired level of prestress was obtained. Transverse deflections of the plate were monitored with a dial extensometer, during application of prestress loads, to avoid the development of eccentricity in load application. Prestressing levels increasing in approximately 1000 psi increments were used to a maximum of almost 17,000 psi.

After establishing the desired level of biaxial prestressing, the transverse load was applied slowly until failure of the plate occurred. Transverse deflections, at the center of the plate, were measured with a dial extensometer during transverse loading for selected specimens.



PRESTRESSING FIXTURE FOR CERAMIC PLATES

FIGURE 1



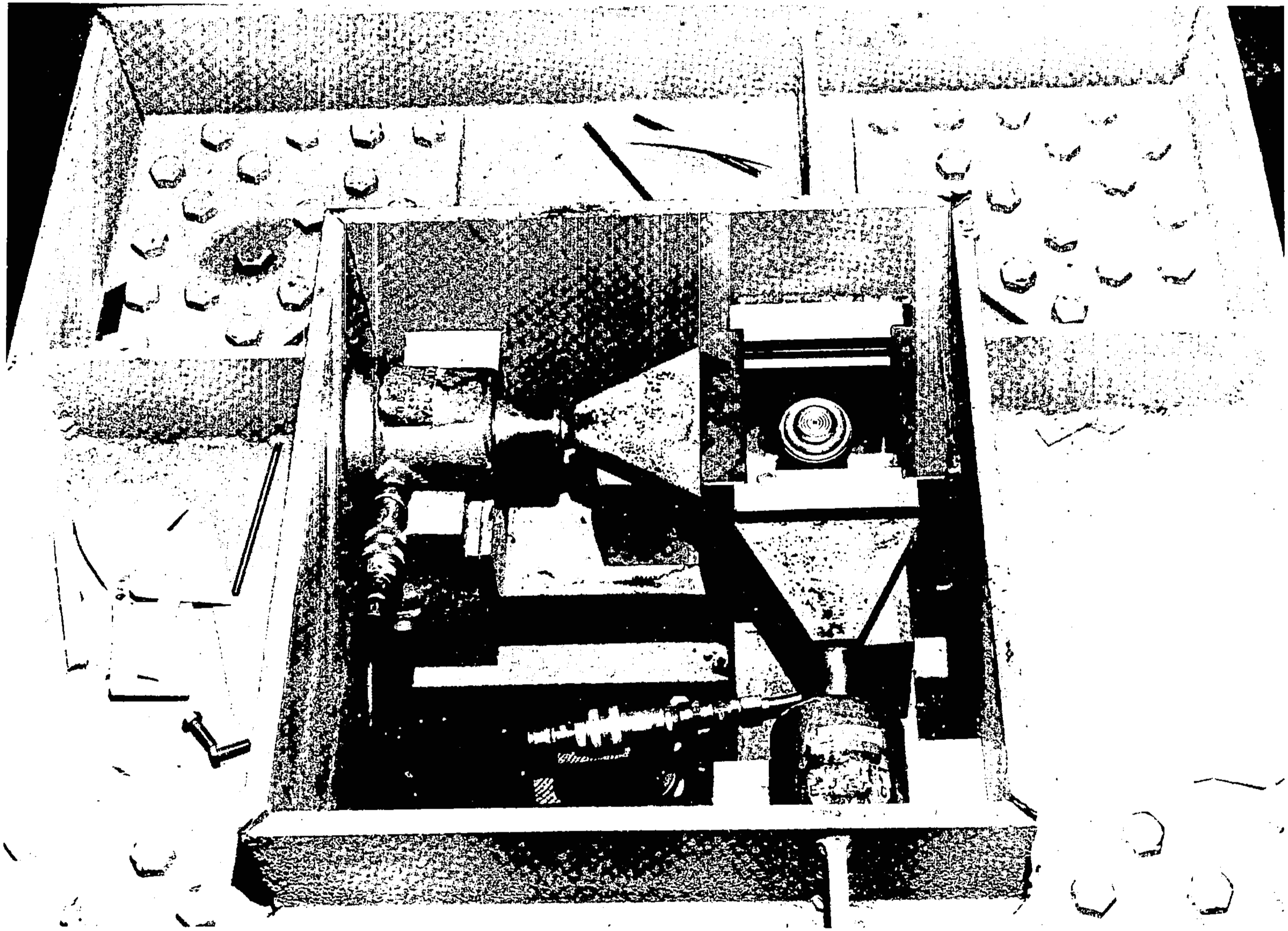
P_{A-X} = PRESTRESSING LOAD IN X-DIRECTION

P_{A-Y} = PRESTRESSING LOAD IN Y-DIRECTION

W = TRANSVERSE LOAD (APPLIED OVER A $1\frac{1}{2}$" CIRCULAR AREA)

LOADING OF A BIAXIALLY PRESTRESSED
CERAMIC PLATE

FIGURE 2



PRESTRESSING FIXTURE SHOWING THE LOADING JACKS

FIGURE 3

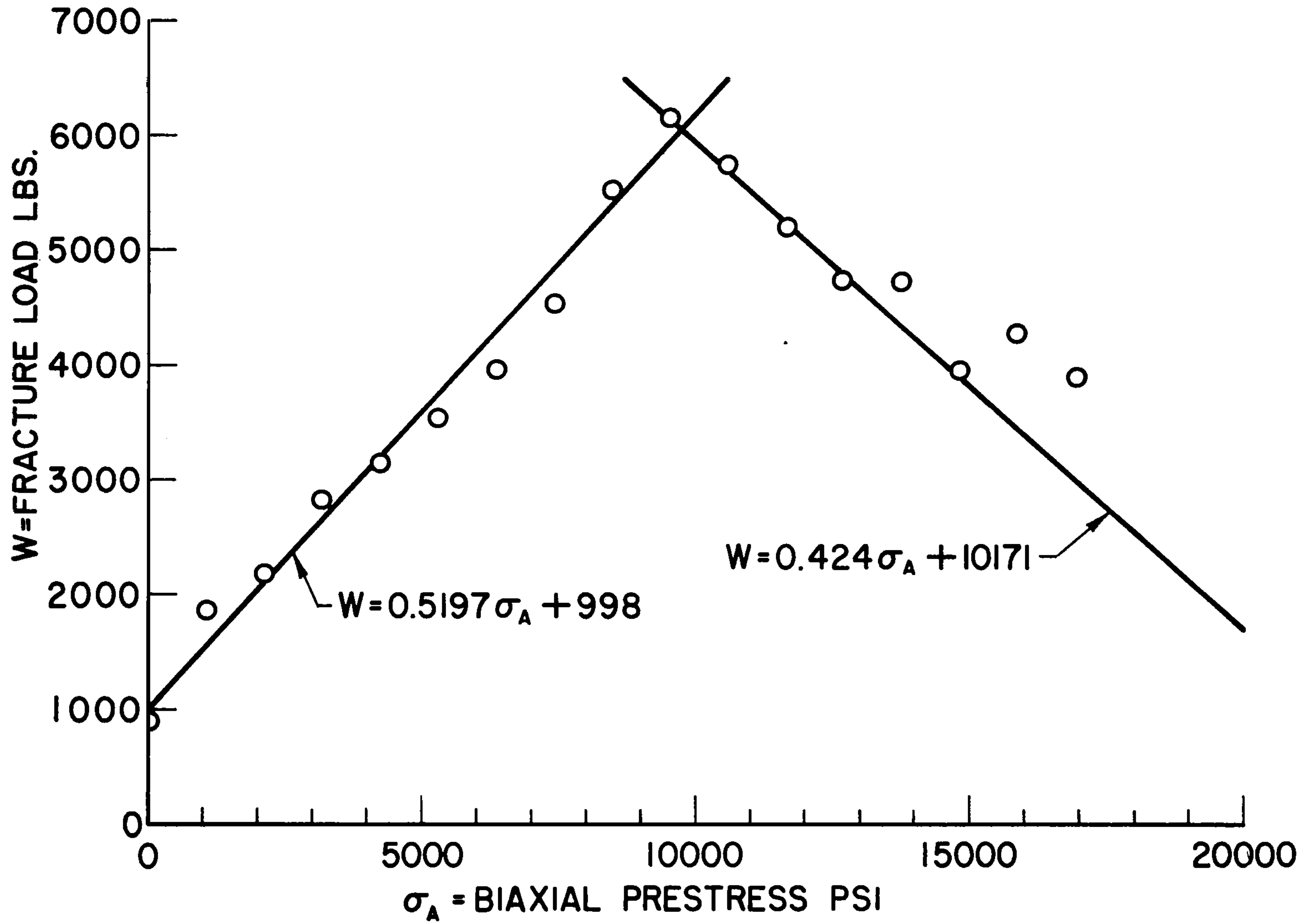
III. RESULTS

In Figure 4 is plotted the average fracture load versus the biaxial prestress. The straight lines drawn through the averages of the experimental points were calculated by the method of least squares, assuming linearity to the left and right of the maximum. Explanation of the reasons for assuming linear relationships appears in the Discussion. In calculations for constructing the straight line, the fracture load at zero prestress was not included. An extrapolation of the straight line to zero prestress gives a fracture load of 998 lbs. as compared with the experimentally determined value of 901 lbs. The experimental point at zero prestress is the average of 14 determinations as indicated in Table I.

TABLE I

FRACTURE LOADS FOR BIAXIALLY PRESTRESSED CERAMIC PLATES

σ_A	W			
Biaxial Prestress psi	Minimum Fracture load. lbs.	Maximum Fracture load. lbs.	Average Fracture load. lbs.	Number of Determination
0	690	1020	901	14
1050	1690	2060	1860	5
2110	2060	2260	2170	7
3170	2650	3040	2830	5
4230	2650	3630	3140	10
5280	2850	4020	3530	10
6340	3440	4420	3960	10
7400	3830	5200	4540	10
8450	5200	5990	5520	5
9510	5790	6970	6140	5
10570	4610	6970	5750	10
11620	3040	6180	5190	15
12680	3830	6180	4730	10
13740	3830	5400	4730	5
14800	3040	4610	3950	5
15850	3040	5790	4300	8
16910	3040	5790	3910	5



TRANSVERSE LOAD PRODUCING FRACTURE OF
BIAXIALLY PRESTRESSED PLATES

(Lines Constructed by Method of Least Squares)

FIGURE 4

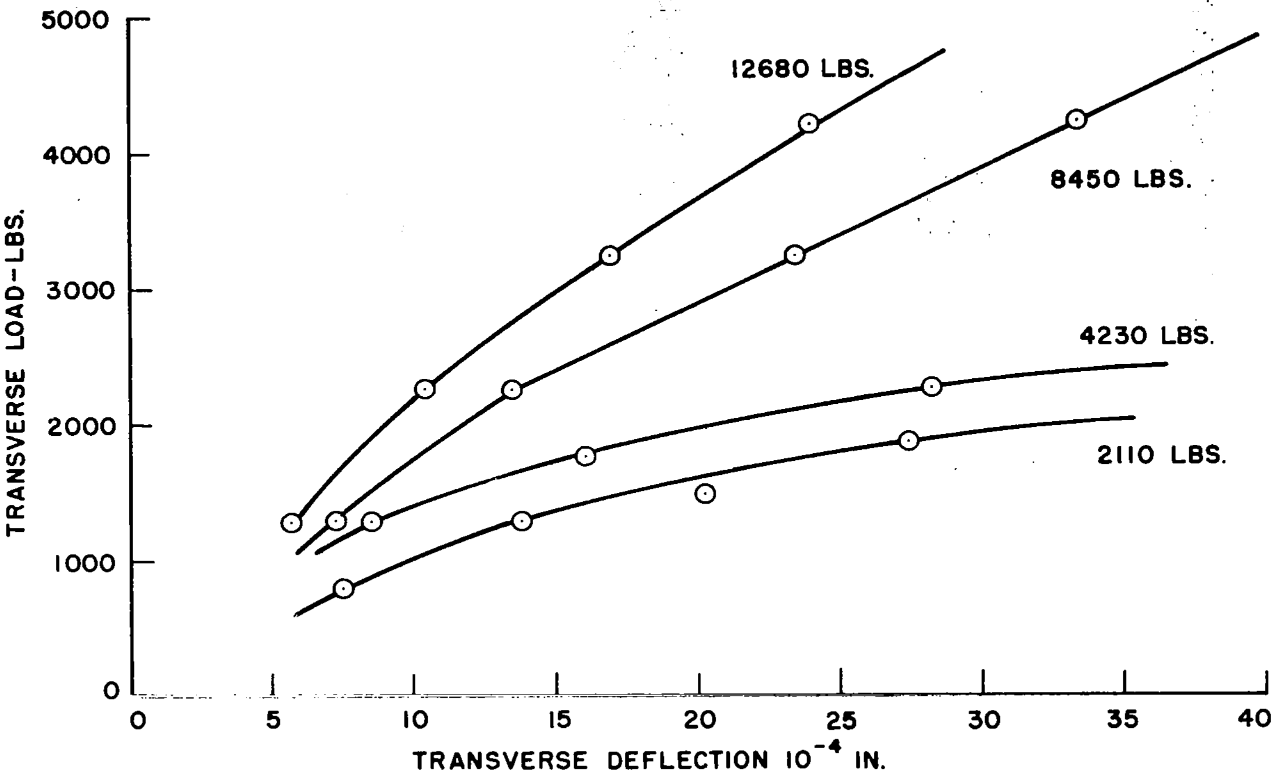
Figure 4 shows that the maximum fracture load was 6150 lbs. at 9500 psi prestress, compared to 901 lbs. at zero prestress, thus giving an improvement of 682%. Table I gives the average value of the experimental points, the number of samples tested, and the range. Figure 5 shows the deflection at the center of the plate as a function of transverse load at various prestress levels. This figure illustrates the significant increase in stiffness with increasing prestressing. The deflection data for prestress levels above 12680 psi were essentially the same.

The nature of the failure of a biaxially prestressed plate was unique; if a substantial level of prestressing existed, the fracture was characterized by formation of a hole in the plate by the penetrating transverse-loading ram. In most such cases, the plate maintained its monolithic integrity after failure and could be removed from the fixture in monolithic form. Figure 6 shows the nature of failure in well-prestressed plates; it will be noted that a concavity was formed on the side of a plate opposite the transverse-loading ram.

IV. DISCUSSION

Significant features of Figure 4 are the apparently linear increase and decrease of the transverse fracture load with prestress, and the resultant maximum fracture load at a unique prestress level. One explanation of these results may be advanced by assuming that the plate undergoes no plastic deformation prior to fracture, and that only elastic deformation occurs (a valid assumption for room-temperature loading of ceramics as confirmed from reference to the literature).

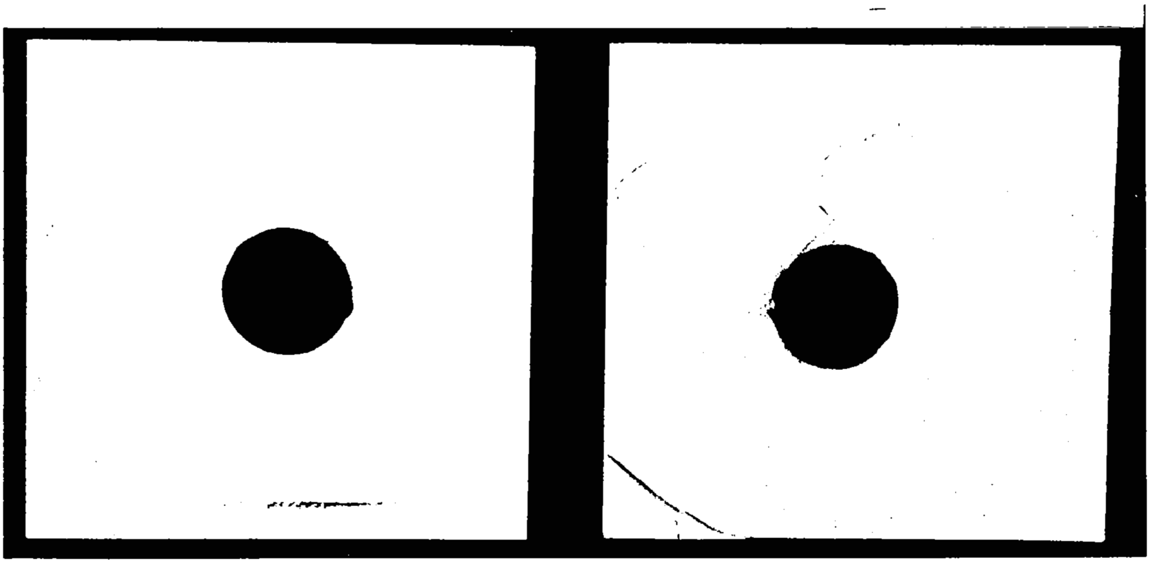
Next, a helpful analogy is provided by the loading of a simply supported beam of rectangular cross-section (Figure 7): the imposition of a load W causes bending, and induces compressive and tensile stresses, with the maximum and equal corresponding stresses occurring in the extreme "fibers" adjacent and opposite to the load W. If uniaxial prestress loads P_A are applied in the direction of the neutral axis X, we may determine the resulting net internal stresses by



TRANSVERSE DEFLECTION, AT THE CENTER OF PLATES, AT VARIOUS PRESTRESS LEVELS

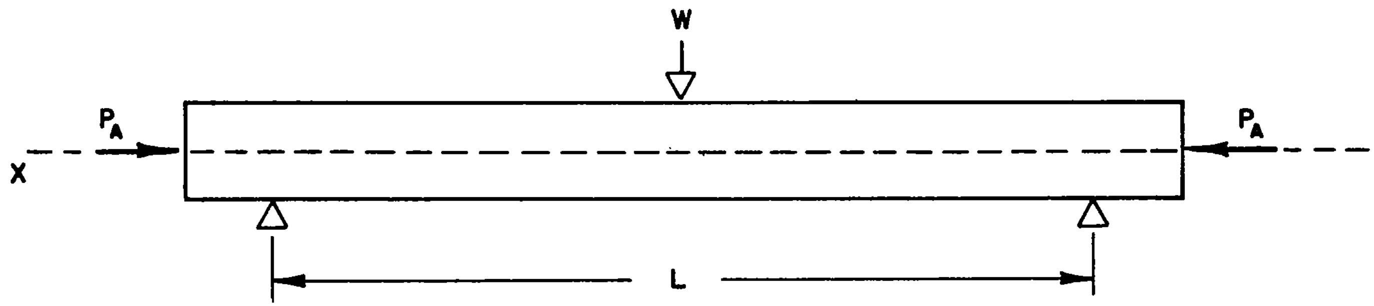
(Each Point is the Average for Three Plates Tested)

FIGURE 5



OPPOSITE FACES OF BIAXIALLY PRESTRESSED
PLATES AFTER FAILURE

FIGURE 6



LOADING OF A UNIAXIALLY PRESTRESSED BEAM

FIGURE 7

superposition; that is, at each position of interest in the beam, the compressive prestress σ_A may be added to the stress σ induced by bending, giving a resulting net stress. Let us now assume that the load W is just sufficient to produce fracture; this will occur if (i) the net stress in the extreme "fibers" opposite the load W exceeds the tensile strength of the material, or if (ii) the net stress in the extreme "fibers" adjacent to the load W exceeds the compressive strength of the material. We may now calculate the transverse load W sufficient to produce fracture by either (i) tensile stress, or (ii) compressive stress, for a specific level of uniaxial prestress (σ_A), providing the tensile strength and compressive strength of the material are known. The results of such calculations for a hypothetical material are shown in Figure 8.

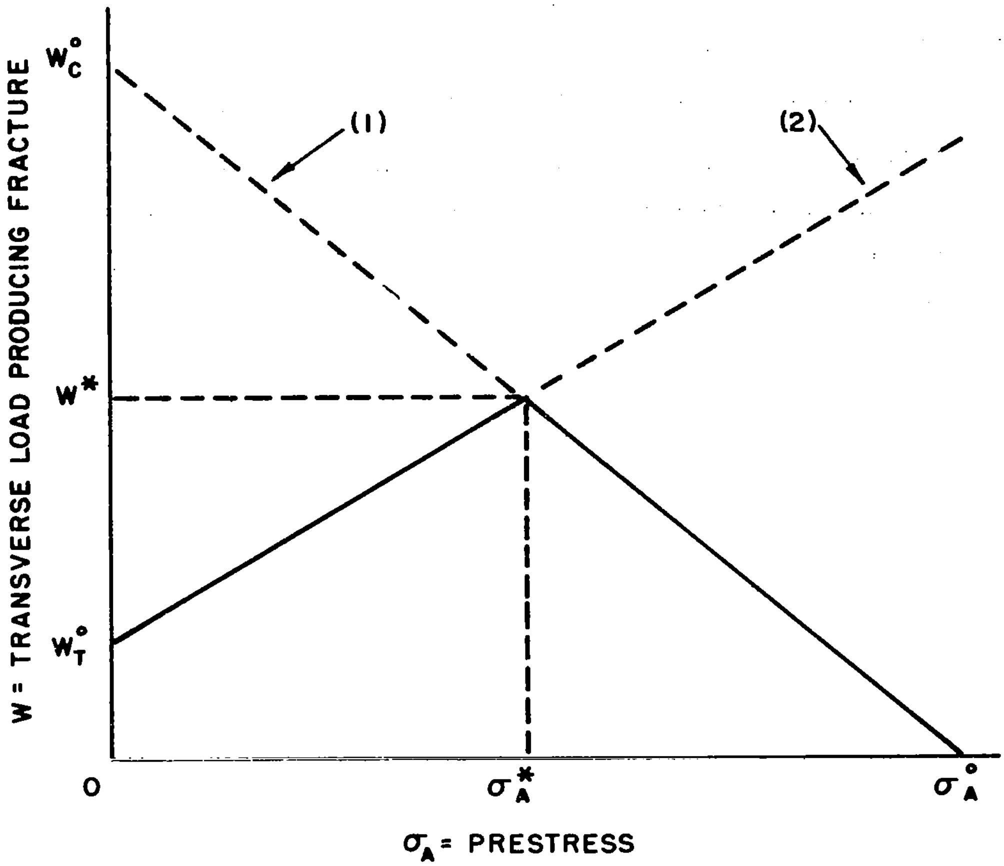
Curve (1) in Figure 8 represents fracture due to compressive stresses (the dashed portion of the curve is hypothetical since, under the conditions specified for this part of the plot, the specimen will fracture due to a crack originating in the region of material under maximum tensile stress). The equation for curve (1) is:

$$- W_c^\circ K = - W K - \sigma_A \tag{1}$$

where W_c° is the load producing compressive failure when no prestress is applied, K is a factor which is a function of the geometry of the sample, the loading conditions and Poisson's ratio, W is the fracture load, and σ_A is the prestress. The slope of curve (1) is $-1/K$, and thus is independent of all properties except Poisson's ratio. σ_A° (shown in Figure 8) is the ultimate compressive strength of the material under prestress alone.

Curve (2) in Figure 8 represents fracture in tension under a transverse load W and with a prestress σ_A. The equation of curve (2) is:

$$W_T^\circ K = W K - \sigma_A \tag{2}$$



FRACTURE LOAD VS. PRESTRESS LEVEL FOR A
HYPOTHETICAL UNIAXIALLY PRESTRESSED BEAM

FIGURE 8

where W_T° is the load producing fracture (from tensile failure) under conditions of zero prestress, and K is the proportionality constant (the same K is applicable in Equations 1 and 2). The slope of curve (2) is $\frac{1}{K}$ (equal, but opposite in sign, to the slope of curve 1).

The optimum prestress level, and the maximum fracture load will occur when curves (1) and (2) of Figure 8 intersect and may be calculated from Equations (1) and (2). Let W^* be the maximum fracture load which occurs at the optimum prestress level σ^*, substitution of these quantities in Equations (1) and (2) and elimination of σ^* between them yields the maximum fracture load:

$$W^* = \frac{1}{2}\left(W_c^\circ + W_T^\circ\right) \tag{3}$$

The optimum prestress level σ^* is obtained by eliminating W^* between the equations and is given by:

$$\sigma_A^* = -\frac{K}{2}\left(W_c^\circ - W_T^\circ\right) \tag{4}$$

Equations (3) and (4) give important quantities necessary to the design of prestressed ceramic members in terms of the properties of the material $\left(W_c^\circ \text{ and } W_T^\circ\right)$ and the loading conditions (K). W_T° may be obtained by measuring the fracture load without prestress. W_c° may be obtained by measuring the fracture load under prestress with no transverse load applied, since $W_c^\circ K = \sigma_c^\circ$. The constant K must be calculated from the loading conditions. For example, for the three point loading of Figure 7,

$$\sigma = \frac{WL}{4z} \tag{5}$$

where σ is the maximum induced compressive or tensile stress, L is the distance between supports, and z is the section modulus. In this case $K = \frac{L}{4z}$, W_T° is the load obtained from transverse loading under zero prestress, and $W_c^\circ = \frac{4z\,\sigma_c^\circ}{L}$, where σ_c° is the compressive strength of the beam. Thus, using the experimentally determined strengths in bending and compression, and knowing the geometry of the beam, the optimum uniaxial prestress and the maximum fracture load of the beam can be calculated.

The analysis, although illustrated by a beam, applies to any prestressing and loading conditions for which the internal stress is a linear function of the loading up to fracture. The main features of the above analysis are directly analogous to the experimental results for biaxially prestressed plates (compare Figures 4 and 8). The experimental data show a maximum fracture load at a unique prestress level (Figure 4), and the fracture curves on either side of the maximum are linear. The above analysis suggests that fractures to the left of the maximum are due to tensile stresses (exceeding the tensile stress of the material) and that the fractures at high prestress levels are due to compressive stresses (exceeding the ultimate compressive stress of the material).

Extrapolation of the tensile failure curve to zero prestress gives 998 lbs. which is in fair agreement with the experimentally determined fracture load of 901 lbs. at zero prestress. Extrapolation of the compressive failure curve to zero transverse load yields a value of 23990 psi, which may be compared with the ultimate compressive strength of the plate under biaxial compressive loading. Unfortunately, the loading-capacity of the hydraulic jacks used did not permit an experimental determination of this value.

The analysis also predicts the result that the slopes of the two straight lines should be equal, and have the value $1/K$ but of opposite sign. The slopes of the curves in Figure 4 are not in good agreement, having values of 0.52 in.^{2} and -0.42 in.^{2}, respectively. However, this difference may be a result of the greater spread in data found at high levels of prestress.

V. SUMMARY

(1) The load-bearing characteristics of ceramic plates, under the conditions of this experimentation, were greatly improved by biaxial prestressing; the optimum improvement was almost 700%.

(2) A plot of the transverse fracture load against the prestress level shows an initial increase of fracture load with increasing prestress; a maximum is reached, following which the fracture load decreases with increasing prestress. These two portions of the curve are approximately linear. An analysis of fracture of a hypothetical uniaxially prestressed beam was presented, the main features of which are directly analogous to the experimental results of this work.

(3) The failure occurring in a biaxially prestressed plate, under the transverse loading of this experimentation, was characterized by the formation of a hole by the penetrating ram. In most cases the ceramic plate maintained its monolithic integrity. When no prestress was applied fracture was characterized by irregular cracking of the plate. At very high levels of prestress complete fragmentation of the plate occurred.

(4) The stiffness of the prestressed plates increased with the level of prestress.

REFERENCES

1. Anderegg, F. O. and C. L. Dalzell, "Prestressed Ceramic Members", Proc. A.S.T.M., 35 (Part II), pp. 447-456 (1935).

2. Anderegg, F. O., "Progress in Prestressing Structural Clay Masonry", Bull. Amer. Ceramic Soc., Vol. 18, No. 9, pp. 323-325 (1939).

3. Shanley, F. R., "Preliminary Investigation of a Prestressed Ceramic Wing", Rand Research Memo., R.M.-598, (January 24, 1951).

4. Johnston, R. D., R. D. Chipman and W. J. Knapp, "Prestressed Ceramics as a Structural Material", J. Amer. Ceramic Soc. Vol. 36, No. 4, pp. 121-216 (1953).

5. Shanley, F. R., W. J. Knapp and R. A. Needham, "Prestressed Ceramic Structures", WADC Technical Report 54-75, O.T.S. (1954).

6. Shanley, F. R., W. J. Knapp and R. A. Needham, "Prestressed Ceramic Structures", WADC Technical Report 54-75, Part II, (January 1955).

7. Clanton, J. R., J. I. Mueller and H. R. Powell, "Structural Tests on a Prestressed Ceramic Beam", The Trend in Engineering, University of Washington, pp. 4-8 (July 1953).

8. Ali, M. A., "Load Bearing Characteristics of Prestressed Ceramic Plates", M.S. Thesis, University of California, Los Angeles (June 1964).

9. Barnett, R. L., P. Hermann and J. Costello, "Prestressed Monolithic and Segmented Brittle Structures", Final Report (Phase I) M6046, Illinois Institute of Technology Research Institute (April 1964).

10. Kallup, C. and S. V. Kastner, "Transverse Strength of Prestressed Beryllia at Elevated Temperature", presented at the 66th Annual Meeting, American Ceramic Society, April 22, 1964. (Also Research Report, Marquardt Corporation, Van Nuys, California, April 1964.)